

NM WAIDS: A Produced Water Quality and Infrastructure
GIS Database for New Mexico Oil Producers
(First Semi-Annual Technical Progress Report)

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ABSTRACT

The New Mexico Water and Infrastructure Data System (NM WAIDS) seeks to alleviate a number of produced water-related issues in southeast New Mexico. The project calls for the design and implementation of a Geographical Information System (GIS) and integral tools that will provide operators and regulators with necessary data and useful information to help them make management and regulatory decisions.

The major components of this system are: 1) databases on produced water quality, cultural and groundwater data, oil pipeline and infrastructure data, and corrosion information, 2) a web site capable of displaying produced water and infrastructure data in a GIS or accessing some of the data by text-based queries, 3) a fuzzy logic-based, site risk assessment tool that can be used to assess the seriousness of a spill of produced water, and 4) a corrosion management toolkit that will provide operators with data and information on produced waters that will aid them in deciding how to address corrosion issues. The various parts of NM WAIDS will be integrated into a website with a user-friendly interface that will provide access to previously difficult-to-obtain data and information.

Primary attention during the first six months of this project has been focused on creating the water quality databases for produced water and surface water, along with collection of corrosion information and building parts of the corrosion toolkit.

Work on the project to date includes:

1. Creation of a water quality database for produced water analyses. The database was compiled from a variety of sources and currently has over 4000 entries for southeast New Mexico.
2. Creation of a web-based data entry system for the water quality database. This system allows a user to view, enter, or edit data from a web page rather than having to directly access the database.
3. Creation of a semi-automated data capturing system for use with standard water quality analysis forms. This system improves the accuracy and speed of water quality data entry.
4. Acquisition of ground water data from the New Mexico State Engineer's office, including chloride content and TDS (Total Dissolved Solids) for over 30,000 data points in southeast New Mexico.
5. Creation of a web-based scale prediction tool, again with a web-based interface, that uses two common scaling indices (Stiff-Davis and Oddo-Thomson) to predict the likelihood of scaling. This prediction tool can either run from user input data, or the user can select samples from the water analysis database.
6. Creation of depth-to-groundwater maps for the study area.
7. Analysis of water quality data by formation.
8. Continuation of efforts to collect produced water quality information from operators in the southeast New Mexico area.
9. Qualitative assessment of produced water from various formations regarding corrosivity.
10. Efforts at corrosion education in the region through operator visits.

Future work on this project will include:

11. Development of an integrated web and GIS interface for all the information collected in this effort.
12. Continued development of a fuzzy logic spill risk assessment tool that was initially developed prior to this project. Improvements will include addition of parameters found to be significant in determining the impact of a brine spill at a specific site.
13. Cleanup and integration of water quality databases.
14. Compilation of both hard copy and online corrosion toolkit material.

PROGRESS AND DISCUSSION OF RESULTS

Database Construction

A key task for this project was the development of dynamic web-accessible databases for storing, managing, accessing, and analyzing data that will eventually be accessed by both web-based queries and GIS-initiated queries. As the data files can be quite large, the system must be efficient and useable by persons with varying degrees of computer literacy. Important advances in the database construction and web system have taken place. Data flows, data processing methods and user interfaces with for the NM WAIDS have all progressed.

Groundwater Database

The data comprising the bulk of the groundwater quality database was obtained from the Office of the State Engineer (NMSEO), Water Rights Division District 2, in Roswell, New Mexico. This data set contains over 30,000 records for southeast New Mexico and actually covers a larger region than is addressed in the NM WAIDS project. The only chemical data available were chloride content and total dissolved solids (TDS), so these will be the only water quality parameters analyzed in this study, unless a significant amount of data from another source is acquired. A second data set was also acquired from the NMSEO's Santa Fe office that contains no quality data, but does have basic positional information along with well depth and groundwater depths. This database covers the entire state and will eventually be used to construct maps showing depths to groundwater, a parameter believed to be important when chemical or brine spills are being considered. Figure 1 shows groundwater chloride contents in the study area for samples from the Roswell database.

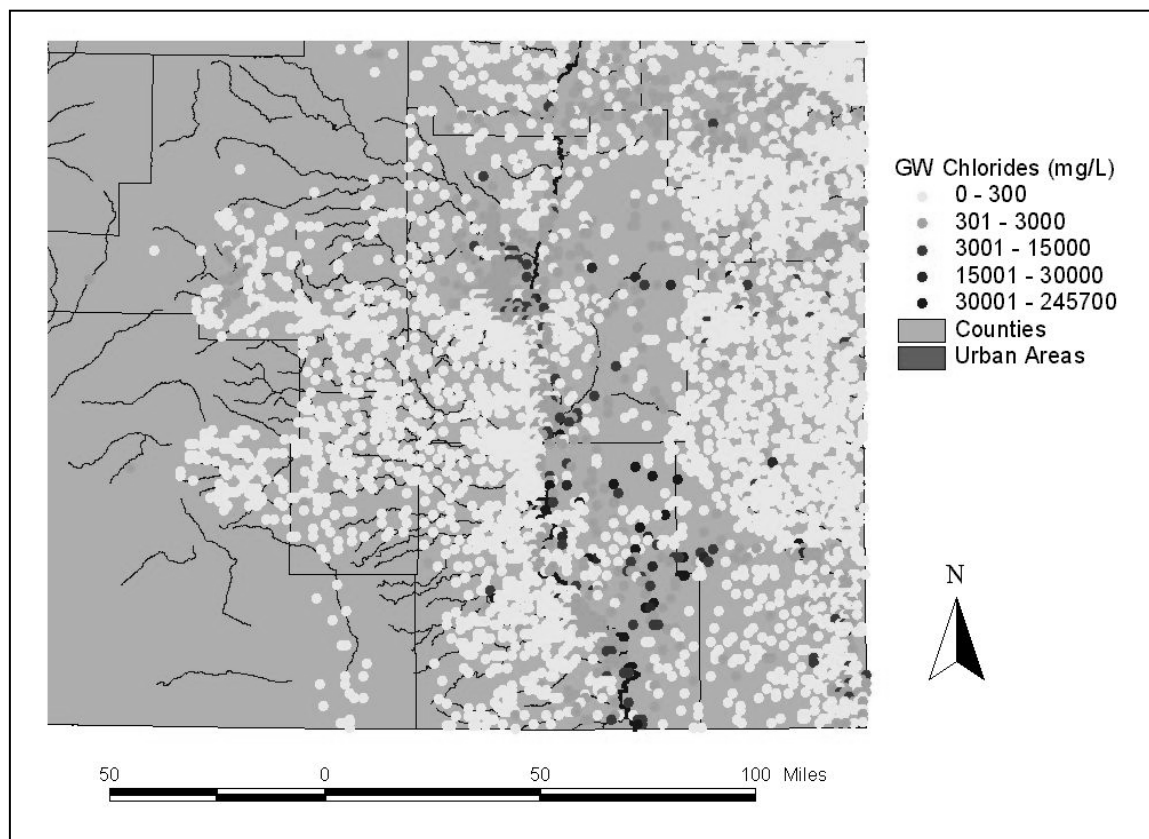



Figure 1. Chloride content of groundwater in southeast New Mexico. Highest salinity samples primarily from near and east of the Pecos River.

Produced Water Quality Database

The Produced Water Quality Database (PWQD) is being compiled from a large variety of source data. A number of  and gas producers in the area were solicited for data, and many have been very generous in sharing this information. Some of the data has been provided in digital format, either as Microsoft Excel spreadsheets, Microsoft Access databases, or simple text files. Much, however, comes from producers as paper forms supplied to them by the various companies employed to run the water analyses. Each data source must be analyzed to determine what kind of data is available and in what format (numeric, text, semi-quantitative), so the correct fields and data definitions can be built into the database structure. Examination of the digital and paper forms revealed that data could be divided into four main categories: general information, general sample properties, anions, and cations. A number of tables and views are used in the database construction: primary tables are the general sample information (items such as sample name, location, formation, physical parameters), anion information (CO₃, SO₄, etc.), and cation information (Ca, Na, Mg, etc). After the initial database was constructed, digital data sets were imported into the database. As new data sets, either paper or digital, are acquired, some modifications to the PWQD may be required, but it is believed that the current structure will accommodate new data types.

Web-Based Data Entry System

One component of the PWQD is a web-based data entry system. This was implemented for two reasons. First, much of the data entry for the initial database was done by student employees. It was more efficient, and also more secure to have these employees work from remote locations and use a system of forms to enter data, rather than having them actually manipulate the database. Users can examine, add, or edit data via the web entry system; however it would be difficult for a user to inadvertently damage the entire database or delete large amounts of information. Another reason for the web entry system is that it is envisioned that producers will eventually be able to enter their own data into the system, should they wish to.

Automatic Data Capture System

A second component of the PWQD, and one which received significant effort in this reporting period, is the Automatic Data Capturing System (ADCS). Because this represents a great improvement in our database-building efforts, this component will be described more thoroughly. The objective of the ADCS is to speed the transfer of data from the multitude of paper forms into digital format, and to incorporate this data into the existing SQL databases.

We have collected over 3000 water quality analysis forms to date. There is an average of 30 fields on each form from which data has to be collected, and there are many types of forms, so the data types are not always the same from form to form. Previous experience with the web-entry system showed that it took at least five minutes per form just to enter the data without any verification. Manual input proved to be impractical for the number of forms we had, and was also prone to significant typographical errors. With the new data capturing system it takes less than a minute for each form if the form is well structured and clear. This time includes any time for manual verification. In some cases, such as forms filled in with cursive hand writing and unstructured forms, it may take up to three minutes depending on how bad the form is. Even in the worst case the time is 50% less than that required for manual entry and verification. On average the total savings on time is more than 60%. Most of the documents presently being processed are of poor quality (some date back to 1950); once processing of the older documents is complete, processing rates will be still higher, leading to greater savings in time and money. An additional advantage is that now there is a digital record of each image, so if there is a question about the data, the actual form image can be examined.

Technology behind the System

OCR (Optical Character Recognition) is a key technology on which an ADCS works. It is the OCR technology that helps translate what is written on a piece of paper into an electronic text or number format. When a paper is scanned, it is made into a digital picture which the OCR software can interpret. The software/hardware system that recognizes characters from a registered image (part of the image from which individual characters to be recognized) can be divided into three operational steps: document analysis, character recognition, and contextual processing.

Document Analysis

Text is extracted from the document image in a process known as document analysis. Reliable character segmentation and recognition depend upon both original document quality and registered image quality. Processes that attempt to compensate for poor quality originals and/or poor quality scanning include image enhancement, underline removal, and noise removal. Image enhancement methods emphasize character versus non-character discrimination. Underline removal erases printed guidelines and other lines which may touch characters and interfere with character recognition and noise removal erases portions of the image that are not part of the characters.

Prior to character recognition it is necessary to isolate or segment individual characters from the text image of the word. Many OCR systems use connected components for this process. For those connected components that represent multiple or partial characters more sophisticated algorithms are used. In low quality or non-uniform text images these sophisticated algorithms may not correctly extract characters and thus, recognition errors may occur. Recognition of unconstrained handwritten text can be very difficult because characters cannot be reliably isolated especially when the text is cursive handwriting. This process of separation of individual character image files is called segmentation. A significant portion of the data we have acquired is handwritten. Fortunately recognition of numeric characters is fairly successful even for handwritten data.

Form Analysis

Two types of documents are typically found in ADC systems; form-based and text-based. For this project, form-based documents were used. Form-based documents have a structured layout with variable and static information. Form-based documents have two primary concerns when using ADCS. One is that for optimum speed and accuracy all fields, graphic elements, separators, etc. have the exact same location on all copies of the form. It is possible to automate the process if the forms fields are not at the same position on all the forms, but it adds an overhead of extra time in manually aligning the zones. Also, forms should have some reference points to help in correction of any skew and removal of linear or nonlinear scanning defects. The most reliable reference points are black squares on the corners or rectifying marks. In the absence of such marks other features like vertical and horizontal lines, table separators, table borders, etc., can be used as reference points.

Figure 2a shows a typical good-quality document from which water quality information is extracted, while Figure 2b shows one of the more difficult documents that was used. Both documents are treated in the way described below, but the second requires more manual verification.

EL PASO NATURAL GAS COMPANY
SAN JUAN DIVISION
FARMINGTON, NEW MEXICO
PRODUCTION DEPARTMENT WATER ANALYSIS

Analysis No. 1-9722 Date 10-24-79

Operator EHFG Well Name SJ 30-6 8 A

Location NW 31-30-7 County Rio Arriba State N.M.

Field _____ Formation _____

Sampled From 1417 W

Date Sampled _____ By _____

Tbg. Press.		Csg. Press.		Surface Csg. Press.	
ppm	epm	ppm	epm	ppm	epm
Sodium <u>106</u>	<u>5</u>	Chloride <u>12</u>	<u>3</u>		
Calcium <u>262</u>	<u>13</u>	Bicarbonate <u>127</u>	<u>2</u>		
Magnesium <u>36</u>	<u>3</u>	Sulfate <u>875</u>	<u>18</u>		
Iron _____		Carbonate <u>0</u>	<u>0</u>		
H ₂ S _____		Hydroxide <u>0</u>	<u>0</u>		
Total Solids Dissolved <u>1120</u>					
pH <u>7.4</u>					
Sp. Gr. <u>1.0021</u> at <u>60°F</u>					
Resistivity <u>580</u> ohm-cm at <u>77°F</u>					

cc: D.C. Adams
R.A. Ullrich
E.R. Faulk
J.W. McCarthy
A.M. Smith
W.B. Shropshire
File
80 Ft
C. Sp. Nan

Scale: epm

(a)

EL PASO NATURAL GAS COMPANY
SAN JUAN DIVISION
FARMINGTON, NEW MEXICO
PRODUCTION DEPARTMENT WATER ANALYSIS

Analysis No. 1-3051 Date JULY 30, 1962

Operator EL PASO NATURAL GAS COMPANY Well Name PETRA NO. 2

Location SW 11-30-7 County RIO ARriba State NW MEXICO

Field ELANCO Formation MESA VERDE

Sampled From HEADQUARTER

Date Sampled JULY 5, 1962 By CONNELLY

Tubing Pressure 930 Casing Pressure 1008 Surface Casing Pressure 246

ppm		ppm	
Sodium <u>6585</u>	<u>286</u>	Chloride <u>595</u>	<u>17</u>
Calcium <u>80</u>	<u>4</u>	Bicarbonate <u>12150</u>	<u>190</u>
Magnesium <u>0</u>	<u>0</u>	Sulfate <u>3300</u>	<u>60</u>
Iron _____		Carbonate <u>170</u>	<u>6</u>
H ₂ S <u>Absent</u>		Hydroxide <u>0</u>	<u>0</u>
Total Solids Dissolved <u>12260</u>			
pH <u>8.75</u>			
Sp. Gr. <u>1.015</u> at <u>60°F</u>			
Resistivity <u>60</u> ohm-cm at <u>60°F</u>			

cc: M. E. Alamy
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E. S. Oberly
L. D. Galloway
R. Fritchard (c)
R. L. Ahrens
A. H. Viescas
File

Scale: epm

(b)

Figure 2. (a) Example of a good, clean water analysis form that is easy to convert to text. (b) Example of a poor quality water analysis form. Note the fuzziness of the type and the many black specks on the page. These make OCR more difficult.

Automatic form processing consists of three stages: batching, template creation, and form input. Batching is simply the separation of forms into batches of forms with an identical layout. Template creation tells the system what information should be grabbed and in which particular place of the document that information is found. After the template creation is done the system is ready to process the all forms that conform to that particular form. Form input can be done either as a batch, where all forms are first scanned and then processed, or it can be done individually, where each form is scanned and processing occurs immediately.

Form input is further divided into four stages 1) Scanning 2) Recognition 3) Verification and 4) Export. In the scanning stage either an automatic document feed (ADF) or flat bed scanner can be used. After scanning the image, any necessary preprocessing of the image, such as image rotation, page orientation detection, and noise reduction is done. After preprocessing, the image is ready for interpretation. The interpretation module first matches the template and the individual fields are recognized. Once the recognition is done verification of the fields is first done automatically by invoking several predefined rules. The program highlights all the fields which are not recognized properly for manual correction. This is the most time-consuming process in the system and the amount of time spent for verification increases drastically if the forms are not clear or if they have lot of noise. After the automatic and manual verifications, the

data is ready for exporting and it can either be directly exported to an ODBC compatible database or saved into a CSV or excel file.

EL PASO NATURAL GAS COMPANY
SAN JUAN DIVISION
FARMINGTON, NEW MEXICO
PRODUCTION DEPARTMENT WATER ANALYSIS

Analysis No. 1 1-8572 Date 2 October 01, 1975

Operator 3 E.P.N.G. Well Name 4 Horton #6

Location 5 County 6 State 7

Field 9 Formation 8 M. V.

Sampled From 10 Bradenhead

Date Sampled 11 09-23-75 by Thomas F. West

Tubing Pressure 12 Casing Pressure 13 Surface casing pressure 14

	ppm	epm		ppm	epm
Sodium	<u>153330</u>	<u>16 145</u>	Chloride	<u>231680</u>	<u>24 47</u>
Calcium	<u>17350</u>	<u>18 17</u>	Bicarbonate	<u>2515</u>	<u>26 0.2</u>
Magnesium	<u>1980</u>	<u>20 2.4</u>	Sulfate	<u>27615</u>	<u>28 117</u>

Figure 3. Example of a form that has been scanned and processed. The numbered boxes are the data fields that are recorded in a database, while the dashed lines surround fields that are reference fields.

Problems Encountered

Groundwater Database

The major problem encountered in the groundwater database construction is the inaccuracy inherent in the quarter/quarter designation used to locate wells in the original data. In the Public Land Survey System (PLSS) used in New Mexico, township lines are horizontal (similar to latitude) and range lines are vertical (longitude). If every section is exactly square, the same size, and the lines are exactly north/south and east/west, an extremely accurate latitude/longitude can be calculated. However, this is seldom the case. Townships are often offset a considerable amount, sections are elongated or shrunk, and half townships and half ranges may be added to certain regions. Additional problems may be encountered should the NM WAIDS system be extended to the rest of the state. Large areas of the state, particularly those covered by Indian reservations or Spanish land grants, are not covered by the PLSS. Calculation of latitude/longitude coordinates in those areas is even more inaccurate because of the loss of the regular survey grid. Finally, many water well locations are not given in terms of an x-y

coordinate, but simply placed in the middle of a quarter/quarter section, regardless of the actual location.

Produced Water Quality Database

Several significant problems were faced in construction of the PWQD. The first of these was the extreme variability of the data provided. At least 30 different form types have been encountered so far, and the types of data available on each of these can vary tremendously. Simple variations, such as designating the amount of a component as either a number, or as a text descriptor (e.g. nil, trace, present, significant) are difficult to distill into database. Additionally, data is presented in a variety of units such as parts per million, percent, milligrams/liter or milli-equivalent per liter. The problem of data variability was surmounted by the creation of a flexible database structure that will allow for change if necessary. Unit conversion routines have been created and eventually will be incorporated into the system so that users can easily switch from one measurement system to another. Also, a method was devised to preserve as much of the water quality information as possible through the use of database fields designed to hold miscellaneous notes. In this way, information that did not easily fit into any of the specified data fields can be recorded.

The second major problem in the PWQD construction was that of data entry. Much of the information was supplied as thousands of pages of paper forms. Some were typed, some handwritten. Student employees were trained in the use of the data entry system, and online instructions are also available in the system. However, data entry is still time-consuming and error-prone. Use of an OCR program, combined with an automated database entry system has significantly improved this process.

The remaining problem to be addressed with the PWQD is that because of the two entry systems, the water quality data is in two different formats. The first is the database produced by the web entry system. The second is that produced by the ADCS. Discrepancies and duplicates exist between the two databases. A substantial amount of work will be required to clean and merge the databases.

GIS Construction

Construction of the NM WAIDS Geographic Information System has commenced. A number of map layers have been created for the pilot area, including layers showing roads, metropolitan areas, rivers and streams, digital elevation models (DEMs), groundwater well locations, and produced water well locations. Current efforts are underway to convert our underlying land grid to the U.S. Bureau of Land Management's (BLM) Geographic Coordinate Data Base (GCDB). This grid is more accurate than the land grid we have been using and will allow us to be consistent with other state and federal agencies using this system. Once the land grid has been implemented, all well locations, including both water and oil and gas wells will be recalculated. The one significant problem that remains with the construction of our GIS is that of infrastructure—pipelines and handling facilities. Public access to this data has been restricted for security reasons.

Corrosion Management Toolkit

A third key area of the NM WAIDS project that was addressed during this reporting period was the Corrosion Management Toolkit (CMT). One of the first tasks was determining the scope, content, structure, and function of the toolkit. It has been determined that the toolkit will consist of the following components:

1. Reference Book: Descriptions of common types of corrosion-related problems, including photos or drawings. This portion will also include possible mitigation approaches. The web version of this component may also include contact information and links to companies that provide these solutions in the Permian Basin area.
2. Formation Water Analysis: A qualitative analysis of produced waters in the region, by formation, with respect to corrosion related problems. Regional variations and trouble spots will be noted, and if enough data becomes available, we will generate maps to graphically depict the variations.
3. Scale Prediction Tools: Online tools that will allow the user to predict scaling tendencies of either a single water or a mix of waters. The tools will allow the user to input their own data, or they can request samples from the PWQD if they lack sample data. A simple online corrosion prediction tool may be provided. However, this is a very complex and not easily-quantified problem; many chemical vendors have spent considerable time and effort developing commercial software products to do this.

Progress

Significant progress has been made in the construction of the Corrosion Management Toolkit.

Scale Prediction Tools

The scale prediction web pages are almost complete. A discussion of the methodology used to create the tools and the web pages themselves follows.

Methodology

All minerals are soluble in water to a limited extent and solubility calculations are used to predict scale formation. The limit of a mineral's solubility is called the solubility product, K_{sp} . Most minerals are salts and will dissociate into ions, for example $\text{NaCl} \leftrightarrow \text{Na}^+ + \text{Cl}^-$. Multiplying the concentrations of the ions together will give the ion product (IP). If the solution is saturated with that mineral and in equilibrium, the ion product will equal the solubility product K_{sp} .

The Saturation Index (SI) is the logarithmic ratio of the ion product and the solubility product, $\text{SI} = \log (\text{IP} / K_{sp})$. In other words, the SI is the log of the actual amount of mineral-forming ions over the solubility of that mineral. Thus, a saturated solution (in equilibrium) will have a SI of 0, an undersaturated solution will have a negative SI, and a supersaturated solution will have a positive SI. In addition, the saturation index has a logarithmic scale. For example, a solution with a SI of 3 is 10 times more oversaturated than a solution with a SI of 2. It is

important to remember that a positive SI does not necessarily mean that scale will form, since the kinetics of scale formation may be too slow; rather, it is an indicator that formation is possible. The solubility constant for any salt will vary with pressure, ionic strength, temperature, and possibly pH. All salts increase in solubility as the pressure is increased, because when a salt is dissolved in water, there is a decrease in volume. As the ionic strength is increased, solubility increases up to a point when the water simply cannot hold any more salt, and then decreases. The effect of temperature on solubility differs with different salts.

In the oilfield, the most common scale-forming minerals are calcium carbonate (calcite), calcium sulfate, usually in the form of gypsum, and barium and/or strontium sulfates. Both barium and strontium have very low solubilities; thus, when barium or strontium and sulfate are present together in water, scale formation is very likely. At atmospheric pressure, barite is about 20 times less soluble than calcite, which is in turn almost 500 times less soluble in water than gypsum¹. However, barium and strontium are not usually major species in natural waters, so calcium carbonate and sulfate scales are much more common.

Many methods of predicting scale exist in the oil industry, including the Langelier method for calcium carbonate, the Stiff and Davis method, the Skilman/McDonald/Stiff method (SMS), and the Oddo and Tomson method. For this project, we have relied on the Stiff-Davis and Oddo-Tomson methods.

Stiff-Davis Method

The Stiff-Davis method is one of the easiest ways to calculate calcium carbonate scaling tendencies (Calcite Saturation Index) in brines². It is valid between temperatures from 0–100°C (32–212°F) and ionic strengths from 0–4. Inputs needed are pH, alkalinity, calcium concentration, and ionic strength. The Stiff-Davis method is very simple, but it may not be accurate if the pH is not measured immediately at the sample site. In addition, it does not take into account the total pressure or amount of dissolved or undissolved carbon dioxide gas.

Skilman/McDonald/Stiff Method

The SMS method predicts the solubility of gypsum scale (NOT the Saturation Index OR the total possible scale formed),³ and is valid between temperatures of 10–80°C (50–176°F) and ionic strengths from 0–6. Inputs needed are ionic strength, and sulfate and calcium ion concentrations. It does not take pressure into account, or any barium or strontium concentrations, which would most likely precipitate out barite (BaSO₄) or celestite (SrSO₄), reducing the available sulfate ion concentration. The solubility constant, K_{sp}, is calculated using the graph of K_{sp} versus temperature and ionic strength (Appendix 15, Patton, 1986). The SMS method can also be used to predict the solubility of barite and celestite scale, if the K_{sp} variation with temperature and pressure are known.

Oddo-Tomson Method

The Oddo-Tomson method is another way of predicting the formation of calcium carbonate and various sulfate scales by calculating SI values.⁴ It is valid between temperatures of 0–200°C (32–392°F), ionic strengths of 0–4.0, and pressures of 1–1380 bar (0–20000 psig)¹. It calculates different saturation indices for the different types of calcium sulfate minerals,

including gypsum ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$), hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$), and anhydrite (CaSO_4). Gypsum is the most common scale former; it occurs at relatively low temperatures. Above about 100°C (212°F), anhydrite is the stable phase; however, hemihydrate can form in temperatures ranging from 90 to 120°C . The Oddo-Tomson method can also predict the formation of barium and strontium sulfate scales. User inputs needed are chemical analysis (including calcium, barium, strontium, bicarbonate, carbonate, and sulfate ions), temperature in $^\circ\text{F}$, pressure in psia (psig + 14.7), and mole percentage of carbon dioxide in the gas phase or, if there is no gas phase, the amount of dissolved carbon dioxide in the water. If the amount of carbon dioxide is unknown but there is an accurate pH measurement, the method uses the pH to calculate the saturation indices.

The Oddo-Tomson method is more accurate than the Stiff-Davis method because it takes pressure as well as temperature and ionic strength into account. In addition, the method does not require a pH measurement, but calculates the pH based on the amount of carbon dioxide gas and bicarbonate in the water. This allows a greater accuracy in calculating the actual saturation index of a water sample, since pH measurements decline in accuracy very quickly after the sample is taken out of its natural environment.

Web Pages

The scale prediction pages consist of the Stiff-Davis Calculation Page, the Oddo-Tomson Calculation Page, and the Mixing Calculation Page. The Stiff page uses the Stiff-Davis method for SI calculation for calcite, and the SMS method for solubility of gypsum and barite. It also calculates the total possible scale amount for gypsum and barite using Eq. 3.16 of Patton (total calcite scale is calculated using a modified version of this equation).¹ The calculations provide the user with both graphs or tables of calcite SI, and gypsum and barite scale solubility, or total possible scale vs. temperature. Each graph has different temperature points because the original solubility data was collected at different temperatures. When using this page, it must first be specified whether the user would like graphs of the solubility or total possible scale. Regardless, the first graph will be the calcite SI vs temperature.

The Oddo-Tomson page uses the Oddo-Tomson method to predict saturation indices for calcite, gypsum, barite and celestite, taking temperature, pressure, and ionic strength into account. This page can also calculate pH values, if one inputs the mole fraction of CO_2 in the gas phase or, if no gas phase is present, the concentration of dissolved CO_2 in mol/L in the water sample. If the pH value is known to be accurate, the measured pH can be used; however, using a measured pH is discouraged because the method was developed partially as a way to calculate saturation indices (and pH) without a measured pH value. This is because changes in temperature and pressure as the water sample is taken from a formation often leads to degassing, which in turn leads to inaccurate pH measurements, even if measured as soon as a water sample is taken.

Mixing of formation waters will often result in some scale formation, whether mixing different waters in a holding tank or injecting incompatible water into a formation. The mixing page will allow a user to mix waters with a known chemical analysis. Users can specify the ratio that the waters are mixed at, and the program will assume complete mixing, resulting in the maximum amount of possible scale. (A mixing ratio of 1:1 will give the maximum possible

scale.) The result will be the chemical composition of the mixed water, before any precipitation occurs. This data can then be plugged into the Odde-Tomson Page to give an idea of what scales will form, and in what amounts.

In all the pages, users can either input their own chemical analyses, or they can first search the database for water samples that can then be used for any of the calculations. This would allow a person to select water analyses from location near their area of interest or from the same formation for use in the calculations. Figures 4– 6 show examples of the inputs and results for these web pages.

Additional work in this task will consist of adding a mixing routine, whereby the user can calculate a water composition that is based on the mixing of two other waters, either by percent or by volume. This resulting mixed water could then again be placed into the scale calculation programs to determine if the mixing of the two waters could potentially cause problems within wellbores or handling facilities. A simple corrosion calculation may also be included if it is determined to be reasonably accurate and useful.

<input type="checkbox"/>	Lease/Well		General Character	pH	8.21	Total hardness		Ionic Strength	0.06334082
				Specific Gravity	1.004	Resistivity		Total Dissolved Solid	

Ions mg/L											
Ca++	14	Mg++	2	Na+	1453	Ba++		Fe++		Sr++	
CO3=	31	HCO3-	1769	SO4=	103	Cl-	1946	OH-			

Oddo Tomson Method		Oddo Tomson Calculate	
Dissolved Gases		Temperature: (F)	
H2S			
O2		Pressure: (psia)	
CO2			
Gas Phase Choice			
<input checked="" type="radio"/> Gas Phase Present Mol% CO2 as decimal, eg		0.29	
<input type="radio"/> Gas Phase Absent			
<input type="radio"/> pH known			
Saturation Index			
Calcite (CaCO3)			
Gypsum (CaSO4 2H2O)			
Hemihydrate (CaSO4 1/2H2O)			
Anhydrite (CaSO4)			
Celestite (SrSO4)			
Barite (BaSO4)			

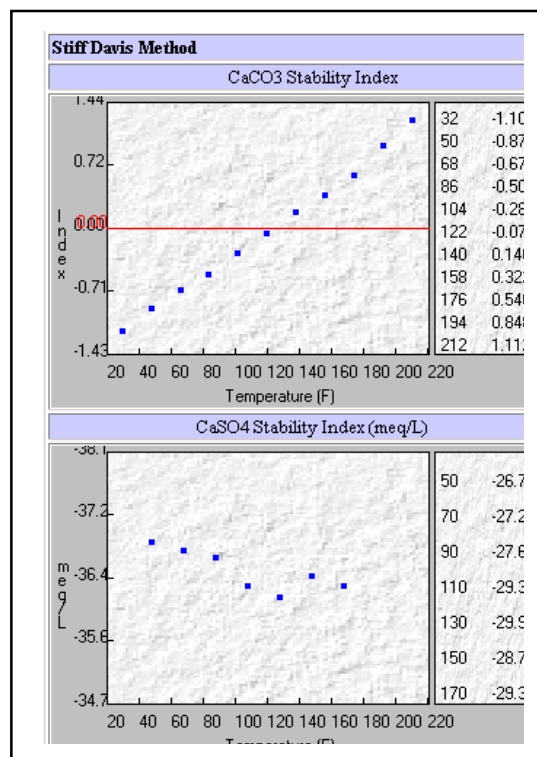
Stiff Davis Method		Stiff Davis Calculate	
Graphics Choice			
<input type="radio"/> Solubility and Actual amount			
<input checked="" type="radio"/> S Index (Actual - Solubility, meq/L)			
<input type="radio"/> Total possible scale in mg/L			
<input type="radio"/> Total possible scale in PTB (A index)			
Clear			

Figure 4. Main page for data entry for Stiff-Davis and Oddo-Tomson scale prediction calculations. Data can either be entered by users from their own information, or a sample can be selected from the PWQD

Probable Mineral Composition Meq/L				Mineral Composition Calculate							
BaCO3	0	CaCO3	0.7	MgCO3	0.16	Na2CO3	0	Fe(OH)2	0		
Ba(HCO3)2	0	Ca(HCO3)2	0	Mg(HCO3)2	0	NaHCO3	29.5	FeCO3	0		
BaSO4	0	CaSO4	0	MgSO4	0	Na2SO4	0	Mg(OH)2	0		
BaCl2	0	CaCl2	0	MgCl2	0	NaCl	31.24	Ca(OH)2	0		

Figure 5. Results of a calculation to determine the probable mineralogical composition of any scale formed by this formation water.

Figure 6. Result of Stiff-Davis calculation for Solubility Index. This shows the results obtained for the above water sample. It can be seen that above temperatures of 122°F,



Formation Water Analysis

Literature Summary of Geochemistry

One of the first steps in understanding the formation water chemistry in the Permian basin was a literature search for existing studies. There are a large number of references about water geochemistry in the Permian basin. These references can be loosely grouped into three categories, which are: 1) older references describing the general hydrology of the upper aquifers and groundwater use in southeast New Mexico; 2) Detailed hydrologic and geochemical studies of the Waste Isolation Pilot Plant (WIPP) site, near Carlsbad, New Mexico, and 3) Geochemical studies of the Palo Duro basin, a basin with similar aged rocks located in the Texas panhandle and separated from the Permian Basin by the Matador Arch.

References about groundwater and surface water in Lea, Eddy, and Chaves counties are quite numerous. However, many of these references are old, and most that concern our study

area cover only the upper fresh water aquifer, not the deep brines. In addition, there is very little interpretation about the origin or history of waters in the basin. Many geochemical studies of the WIPP site, near Carlsbad, New Mexico, have been done. These go into great detail about the Rustler and Salado Formations of the Ochoan series, including major and minor solutes and stable isotope data of the waters. Unfortunately the study area of these reports is much smaller than our pilot area, encompassing only about 1600 km², an area including and surrounding the actual WIPP site. There are several good studies of water geochemistry in the Permian Basin in Texas, including the Palo Duro basin, located in the Texas panhandle. Although they are outside of the pilot study area in southeast New Mexico, they were quite useful as interpretive aids.

Bassett and Bentley⁵ used drill-stem test (DST) data from petroleum wildcat wells to find pressure (head) and transmissivity of the saline deep basin aquifer, and found the hydrodynamics of the Palo Duro basin showed a general decline of head from west to east, following the topographic dip from the Rocky Mountains. Studies by Fisher and Kreidler⁶ further analyzed the saline deep basin aquifer of the Palo Duro basin by using four wells drilled for the U.S. Department of Energy Salt Repository Program and two wells drilled by independent oil and gas companies. Samples from these wells were analyzed for major, minor, and trace ions, as well as isotopic compositions. Formation waters are Na-Cl brines that contain between 124-290 g/L TDS. They fitted their data to hydrodynamic models, which suggest that the basin has been completely flushed by meteoric water, and thus brine chemistry has evolved strictly through water-rock interactions. Chemical and isotopic compositions of the samples suggest two groups of waters: western Palo Duro basin samples, and eastern and central Palo Duro basin samples.

Stueber and others⁷ examined waters in carbonates in the San Andres-Grayburg, Wolfcamp, Pennsylvanian, and Devonian formations in the Central Basin platform in west Texas. They looked at chemical and isotopic signatures from these waters and found basically two groups of waters. The first group, loosely labeled saline meteoric water, includes samples from the San Andres Formation and Devonian limestones. This group has salinities of 26-59 g/L and $\delta D - \delta^{18}O$ values in the same range as modern precipitation and groundwater in the Ogallala aquifer. This water probably acquired its salinity from halite dissolution, shown by Na, Cl, and Br concentrations. The second group of water samples, called modified evaporitic marine brines, is from Pennsylvanian and Wolfcamp limestones. These samples are more saline, with salinities of 70-215 g/L and are apparently a mixture of two fluids, most likely highly evaporated seawater and saline meteoric water similar to the first group waters. These modified evaporitic marine brines were the dominant fluids in Paleozoic carbonates until the late Tertiary, when the tectonic uplift began 5-10 Ma, apparently causing meteoric water to flow into deeper strata. These samples were all taken from formations composed of carbonate, in the form of calcite or dolomite. The different groups are also delineated using TDS and ratios of some major ions, including Cl^-/SO_4^{2-} and Ca^{2+}/Mg^{2+} ratios. The two different Ca/Mg ratios may or may not have any significance, because all the samples were from carbonate formations. The Cl^-/Na^++K^+ ratio, in conjunction with the TDS, was also looked at. Although there is some separation between groups, it is mostly a function of the TDS; there is not enough difference between the Cl^-/Na^++K^+ ratios to separate the two groups. Stueber did not include HCO_3^- in his description, so that ion is ignored; however this seems reasonable considering the highly dynamic nature of both the pH and HCO_3^- concentration when a produced water sample is taken. Figure 7 shows the distinct groupings of water chemistry, particularly in the Ca/Mg vs TDS plots.

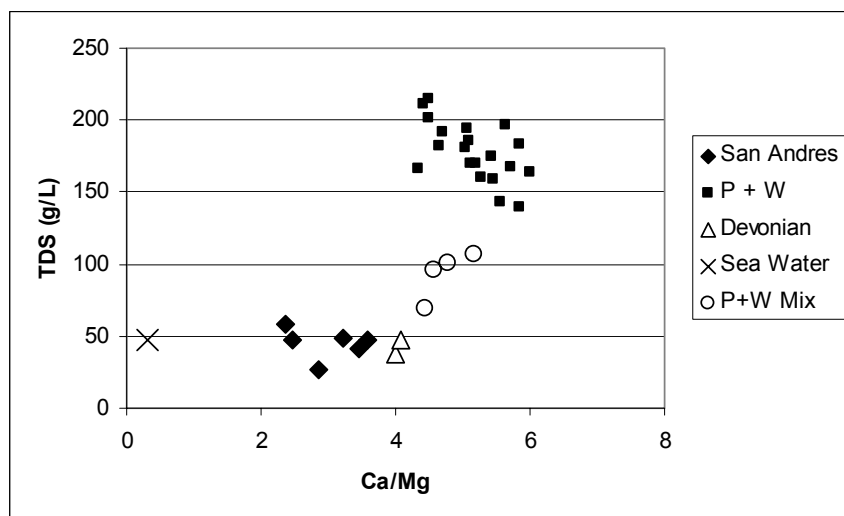
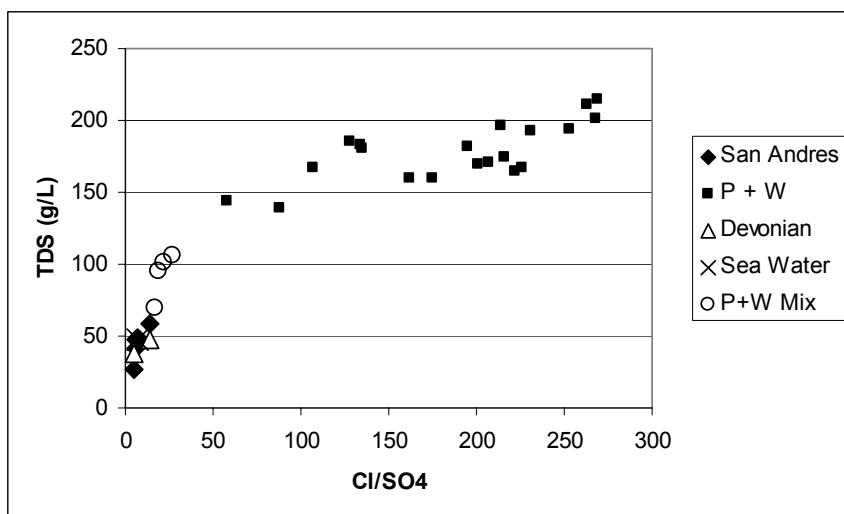


Figure 7. Geochemistry of produced waters from the Permian Basin of west Texas, using the analysis of Stueber and others.⁷ P + W symbolizes Pennsylvanian and Wolfcamp Formation waters. There is a clear difference between these waters and those derived from the San Andres Formation.



We have found that it is possible to use a similar procedure for Permian Basin produced water analyses obtained from the USGS produced water database. Samples were analyzed by individual formation, and again, four distinct groups were seen. The first group corresponds with the first group described by Stueber and others,⁷ saline meteoric water. This group has a TDS of less than 75 g/L, a Cl/SO₄ ratio of less than 50, and a Ca/Mg ratio between 2-4. The second group also corresponds with the second group of Stueber et al., the modified evaporitic marine brines, and has a TDS of 125 g/L or above, a Cl/SO₄ ratio greater than 50, and a Ca/Mg ratio between 4 and 7. The third group is a mixture of the first two groups. It has a TDS between 75 and 125 g/L,

a Cl/SO₄ ratio less than 50, and a Ca/Mg ratio between 4 and 6. The fourth group includes all the samples that do not fall into the other three. The next step in our analysis will be to examine samples for regional variability in water chemistry, using the sample groupings derived from the above exercise.

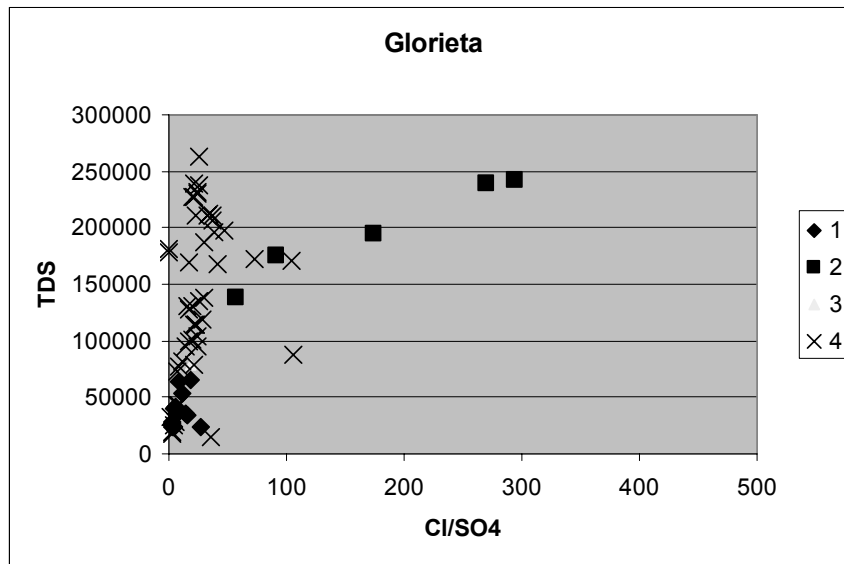
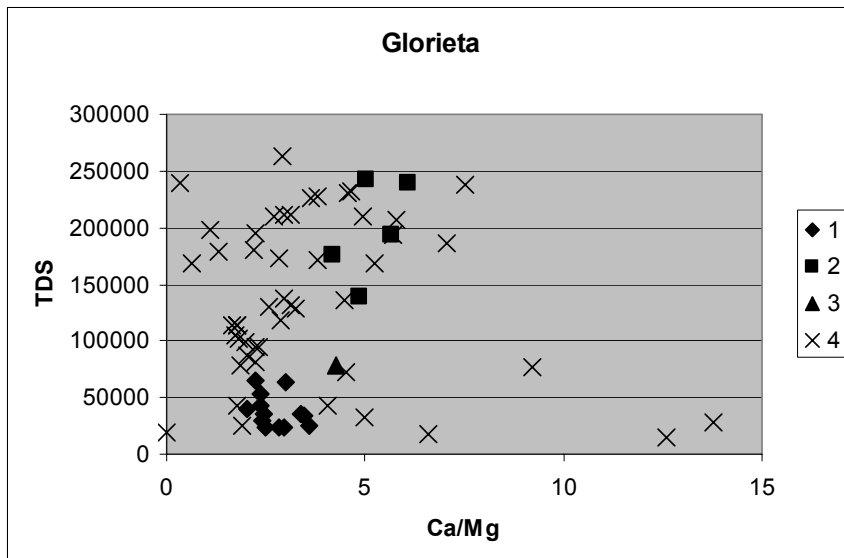


Figure 8. Geochemistry of produced waters from the Permian Basin of New Mexico, using the analysis of Stueber and others.⁷ Analyses are from the USGS database of produced waters. Although there is more scatter than seen in the Stueber analysis from west Texas, there are still distinctive groups that probably represent waters of different origins. The next step in this analysis will be mapping these groups geographically to see if there are any spatially-related trends in water geochemistry. Waters in this graph are all produced from the Glorieta Formation.



Reference Book

Significant progress has also been made in the construction of the reference book. Visits both to operators in the region and to the chemical vendors have provided us with a number of examples, photograph, and drawings of corrosion and scale. Additionally, we have been granted permission to use some of this material, both graphical and text, in the construction of the reference book.

We have intensified our efforts to contact operators and chemical companies for information regarding corrosivity of specific formation waters. In March, a letter was sent to approximately 100 service companies and chemical vendors who operate in the Permian Basin. In this letter, workers familiar with the area were asked to fill out a form with information about various formations. A sample of this form is seen in Figure 9. Letters are being followed up with phone calls, and we have received a number of responses to the survey. Results of this effort will be presented in the next semiannual report.

PRODUCING FORMATIONS OF SOUTHEAST NEW MEXICO											
Formation	Corrosivity					Scaling tendency					Localized problem? (what/where)
	Overall	H ₂ S Y or N	CO ₂ Y or N	Micro- bial	Other	CaCO ₃	CaSO ₄	Asphalte ne	Paraffin	Other	
Rustler											
Salado											
Yates											
Seven Rivers											
Queen											
Grayburg											
San Andres											
Glorieta											
Leonard											
Clearfork											
Delaware											
Wichita											
Abo											
Wolfcamp											
Bone Spring											
Cisco											
Canyon											
Strawn											
Atoka											
Morrow											
Devonian											
Fusselman											
Simpson											
Ellenburger											

Figure 9. Form that was sent to various Permian Basin operators and chemical companies requesting information about corrosivity and scaling tendencies of various formation waters.

Mapping Aquifer Thickness

One of the tasks for this project includes the creation of a tool that will enable operators to determine the relative seriousness and degree of response required for a brine spill at a particular location. It has been determined that one of the most important parameters for this determination is the thickness of the aquifer at a given location. This information has not been published in a form that is easily quantified and placed into a GIS system, so this became a necessary task for completion of the project. The primary aquifer in southeast New Mexico is the Ogallala, and possibly Dockum Formations of Quaternary and Tertiary age. The bottom of the aquifer is formed by the “redbed surface” described by Nicholson and Clebsh⁸ and a contour map of the redbeds in feet above sea level is found in Plate 1 of Nicholson and Clebsh⁸. This map was scanned and converted to an image file, which was used for the rest of our aquifer thickness calculations. Contours were digitized using ArcGIS and the resulting digital contour plot was turned into a grid using “topogrid,” an Arc command that interpolates using a method similar to splining.

The top of the aquifer was found by mapping the water surface, which required several steps. The first step was to determine the depth to water using well data downloaded from the NMSEO website (<http://www.seo.state.nm.us/water-info/index.html>). It was necessary to convert the data to latitude/longitude coordinates. The data was in feet below the surface, so in order to find the aquifer thickness, the land surface elevation was needed. This was obtained by use of a digital elevation map (DEM) provided by the New Mexico Bureau of Geology and Mineral Resources. Then, the depth to water was subtracted from the land surface grid and then a surface (grid) was interpolated using both kriging and inverse distance weighting (IDW) methods. Unfortunately, the resultant grids contained numerous “bull’s-eyes”—artifacts due to poor sample distribution because the wells were spaced quite far apart in the required area.

The redbed surface was subtracted from the water surface, and the resulting grid showed that a large percentage of the area had negative values, i.e., the redbed surface was above the water surface. Surfaces obtained by subtracting the water surface from the land surface (resulting in the thickness of the unsaturated zone) also produced negative values. A second data set with denser well spacing in the area delineated by the original redbed map was obtained. After this data set was cleaned by removing all “zero” data points, it was kriged to produce the depth of the unsaturated zone. When this grid was subtracted from the land surface to get the water surface, it was encouraging to see that the highest and lowest elevations of the water surface were greater than the highest and lowest elevations of the redbed surface.

Finally, the redbed surface was subtracted from the water surface to get the aquifer thickness. Unfortunately, although there was some improvement in the new grid, it was still about half negative values, implying that no aquifer was present. Looking at a grid of land surface – redbed surface (i.e., depth to redbed) shows that in areas, the redbed surface is quite near or even up to 20 feet above the ground surface in the original area of the contour map, so it makes sense that there would probably be more negative values in the aquifer thickness grid. Unfortunately, the data from the NMSEO is not sufficiently detailed in terms of defining what formation a particular well is producing water from. It is likely that in areas, the groundwater is probably coming from the redbeds or deeper formations rather than the Ogallala aquifer. Further research is necessary to determine the answers to this problem.

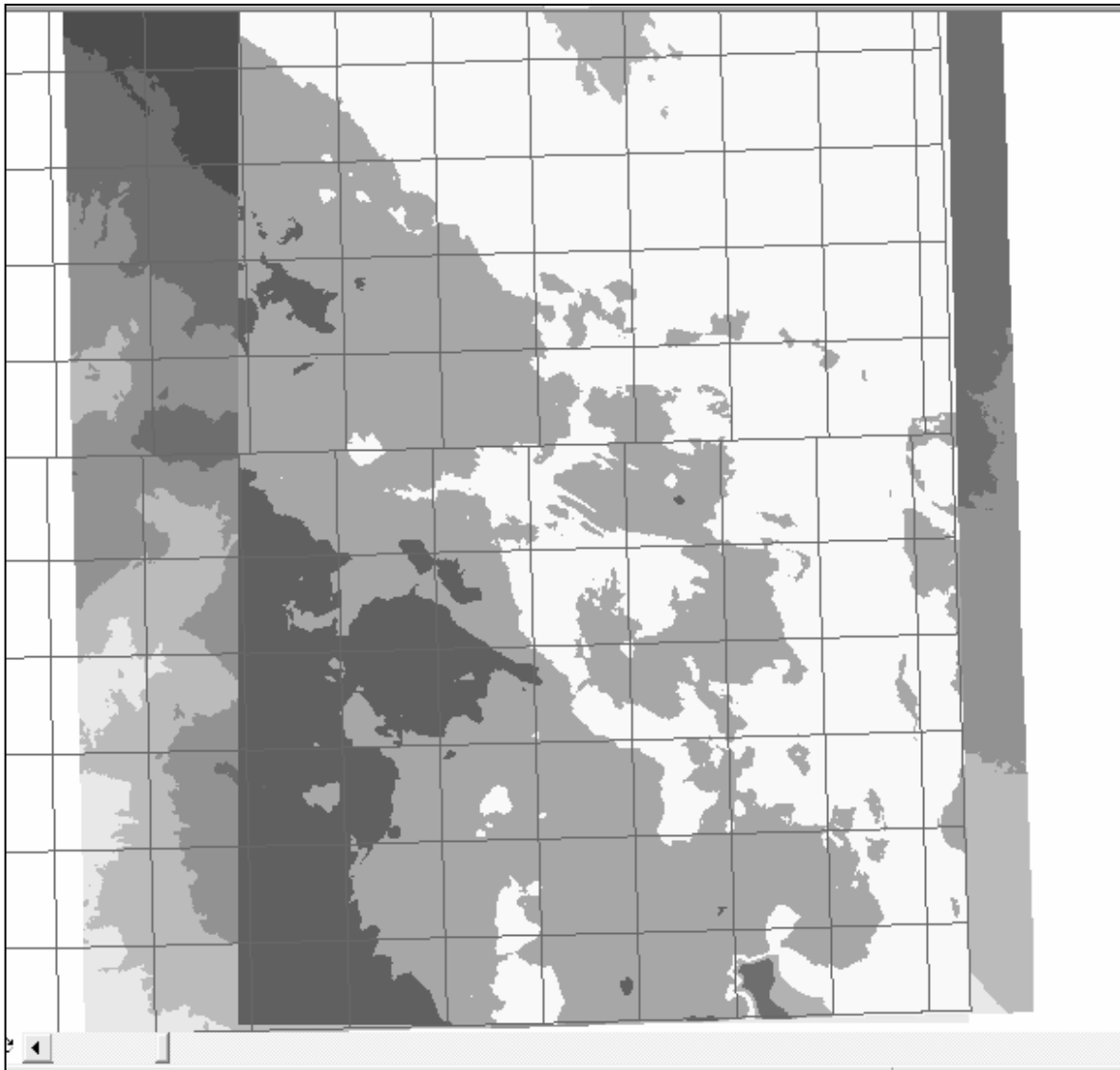


Figure 10. Map showing aquifer thickness in southeast New Mexico. Dark gray areas are those which appear to have a negative thickness, meaning that the water in that area is probably being produced from some other formation.

CONCLUSIONS

A great deal of progress has been made in all phases of the NM WAIDS project. During the past twelve months, we have assembled databases of both produced water quality and groundwater quality, created a web-based data entry system that allows remote users to add data to the PWQD, and created an automatic data capturing system to allow for more accurate data

collection. We have obtained a great deal of produced water chemical data, contacted many Permian Basin operators on corrosion and other water-related issues, and created a web-based tool to predict scale type and probability based on two of the most commonly-used industry methods. We have also begun the process of assembling qualitative water quality information that will be examined for variability by formation, region, and type of problem. Geographic coordinates have been created for all sample locations with sufficient information and we have assembled other pertinent information such as base maps for roads, metropolitan areas, political boundaries, geology, hydrology, and similar data. Aquifer thickness for the area, a possible key parameter in evaluation of brine spills, has been calculated.

Permian Basin operators have been helpful and interested in our work. Yates Petroleum Corporation of Artesia has been particularly generous in the sharing of information, time, and source codes that were a partial basis for the scale calculation tools.

Work is progressing in a timely fashion. The greatest hurdles have been in assembling and entering data for the produced and ground water quality databases, and in cleaning up these databases so that the data is as accurate as possible. The next few months will see the creation of the web site and assembly of the many GIS maps that have been used for water analysis. Two different fuzzy tools that have been examined by various members of the NMOCD and the NMOGA Chlorides working group will be deployed within the GIS, although neither of these tools will necessarily be the tool that is finally approved by the NMOCD and NMOGA.

REFERENCES

1. Patton, C.C., Applied Water Technology, Campbell Petroleum Series, Norman, Oklahoma, 1986.
2. Stiff, H.A., and Davis, L.E., A method for predicting the tendency of oil field waters to deposit calcium carbonate. Transactions AIME, 195, 213-216, 1952.
3. Skillman, H.L., McDonald, J.P. Jr., and Stiff, H.A. Jr., A simple, accurate, fast method for calculating calcium sulfate solubility in oil field brine, presented at the Spring Meeting of the Southwestern District, API, Lubbock, Texas (March 12-14, 1969).
4. Oddo, J.E., and Tomson, M.B., Why scale forms in the oil field and methods to predict it, SPE Paper No. 21710, Production Operations Symposium, Oklahoma City, 1991.
5. Bassett, R. L., Bentley, M. E., 1982. Geochemistry and hydrodynamics of deep formation brines in the Palo Duro and Dalhart basins, Texas, USA. Journal of Hydrology 59, 331-372.
6. Fisher, R. Stephen, Kreitler, Charles W, 1987. Geochemistry and hydrodynamics of deep basin brines, Palo Duro Basin, Texas, USA. Applied Geochemistry, 2, 459-476.
7. Stueber, A. M., Saller, A. H., Ishida, H., 1998. Origin, Migration, and Mixing of brines in the Permian Basin: Geochemical evidence from the eastern central basin platform, Texas. AAPG Bulletin 82, 9, 1652-1672.
8. Nicholson, A. Jr. and Clebsch, A. Jr., Geology and ground-water conditions in southern Lea County, New Mexico: Ground-water Report. Technical Report 6, State Bureau of Mines and Mineral Resources, Socorro, NM, 1961.

BIBLIOGRAPHY

- Oddo, J.E., and Tomson, M.B., Why scale forms in the oil field and methods to predict it, SPE Paper No. 21710, Production Operations Symposium, Oklahoma City, 1991.
- Oddo, J.E., and Tomson, M.B., Algorithms can predict; inhibitors can control NORM scale, Oil and Gas Journal, 92, 1, 33-37, 1994.
- Patton, C.C., Applied Water Technology, Campbell Petroleum Series, Norman, Oklahoma, 1986.
- Skillman, H.L., McDonald, J.P. Jr., and Stiff, H.A. Jr., A simple, accurate, fast method for calculating calcium sulfate solubility in oil field brine, presented at the Spring Meeting of the Southwestern District, API, Lubbock, Texas (March 12-14, 1969).
- Stiff, H.A., and Davis, L.E., A method for predicting the tendency of oil field waters to deposit calcium carbonate. Transactions AIME, 195, 213-216, 1952.

LIST OF ACRONYMS AND ABBREVIATIONS

NM WAIDS – New Mexico Water and Infrastructure Data System
GIS – Geographic Information System
TDS – Total Dissolved Solids
NMSEO – New Mexico State Engineer’s Office
PWQD – Produced Water Quality Database
ADCS – Automatic Data Capture System
OCR – Optical Character Recognition
ADF – Automated Document Feed
ODBC – Open Database Connectivity
CSV – Comma Separated Variable
PLSS – Public Land Survey System
GCDB – Geographic Coordinate Database
CMT– Corrosion Management Toolkit
SMS – Skillman/McDonald/Stiff
IP – Ion Product
SI – Saturation Index
 K_{sp} – Solubility Product
DEM – Digital Elevation Model
WIPP – Waste Isolation Pilot Project
IDW – Inverse Distance Weighting
NMOCD – New Mexico Oil Conservation Division